



Fermi National Accelerator Laboratory

FERMILAB-Conf-97/329-E

D0

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Boaz Klima
For the D0 Collaboration

*Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510*

October 1997

Published Proceedings of the *International Europhysics Conference on High Energy Physics (EPS'97)*,
Jerusalem, Israel, August 19-25, 1997

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Searches for First Generation Leptoquark Pair Production in $\bar{p}p$ Collisions at DØ

Boaz Klima (klima@fnal.gov) (for the DØ collaboration)

Fermilab, Batavia, Illinois, U.S.A.

Abstract. We have searched for the pair production of first generation scalar leptoquarks using the full data set (123 pb^{-1}) collected with the DØ detector at the Fermilab Tevatron during 1992–1996. We observe no candidates, consistent with the expected background. We combine these new results from the $ee + \text{jets}$ and $e\nu + \text{jets}$ channels with the published $\nu\nu + \text{jets}$ result to obtain a 95% CL upper limits on the LQ pair production cross section as a function of mass and β , the branching ratio to a charged lepton and a quark. Comparing to the NLO theory predictions, we set 95% CL lower limits on the LQ mass of 225, 204, and 79 GeV/c^2 for $\beta = 1, \frac{1}{2}$, and 0, respectively. The results of this analysis rule out an interpretation of the excess of high Q^2 events at HERA as leptoquarks with LQ mass below 200 GeV/c^2 for values of $\beta > 0.4$.

1 Introduction

Leptoquarks (LQ) are hypothesized exotic color-triplet bosons which couple to both quarks and leptons. They appear in extended gauge theories and composite models and have attributes of both quarks and leptons such as color, fractional electric charge, and lepton and baryon quantum numbers [1]. Leptoquarks with universal couplings to all flavors would give rise to flavor-changing neutral currents and are severely constrained by studies of low energy phenomena [2]. Therefore, only leptoquarks which couple within a single generation are considered. The H1 and ZEUS experiments at HERA have reported an excess of events at high Q^2 in e^+p collisions [3] [4]. One possible interpretation of these events is production of first generation leptoquarks at a mass near 200 GeV/c^2 [5].

Leptoquarks would be dominantly pair-produced via strong interactions in $\bar{p}p$ collisions, independently of the unknown LQ- l - q Yukawa coupling. Each leptoquark would subsequently decay to a lepton and a quark. For first generation leptoquarks, this leads to three possible final states: $ee + \text{jets}$, $e\nu + \text{jets}$ and $\nu\nu + \text{jets}$, with rates proportional to β^2 , $2\beta(1-\beta)$ and $(1-\beta)^2$, respectively, where β denotes the branching fraction of a leptoquark to an electron and a quark (jet).

Lower limits on the mass of a first generation leptoquark were published by the LEP experiments [6], by CDF and DØ [7], and by H1 [8].

This report describes a search for the pair production of first generation scalar leptoquarks in the $ee + \text{jets}$ and $e\nu + \text{jets}$ final states using 123 ± 7

pb^{-1} of data collected by DØ at the Fermilab Tevatron with $\sqrt{s} = 1.8$ TeV during 1992–1996. A similar search was conducted by the CDF collaboration [9]. The DØ results reported in this article are described in Refs. [10] and [11]. The DØ detector and data acquisition system are described in detail in Ref. [12].

2 The $ee + \text{jets}$ Channel

A base data sample of 101 events with two electrons and two or more jets was selected. The electrons ($E_T^e > 20$ GeV) were required to be separated from jets ($E_T^j > 15$ GeV). Events whose ee invariant mass lies within the Z boson mass region were rejected. The efficiency of the trigger used to collect the base data sample exceeded 99% for the leptoquark mass range addressed by this analysis.

Monte Carlo (MC) signal samples were generated for leptoquark masses between 120 and 260 GeV/c^2 using the ISAJET event generator and a detector simulation based on the GEANT program. Leptoquark production cross sections were taken from the recently available next-to-leading order (NLO) calculations [13]. The primary backgrounds to the $ee + \text{jets}$ decay mode are Drell-Yan+2 jets production (DY), $t\bar{t}$ production, and misidentified multijet events. The ISAJET DY cross section normalization was fixed by comparing it with $Z + 2$ jets data. The DØ measured $t\bar{t}$ production cross section of 5.5 ± 1.8 pb [14] was used for top quark MC HERWIG events. The multijet background was estimated directly from data [10].

To search for leptoquarks, a random grid search method was used to optimize cuts on the data and MC samples. Consistent results were obtained using a neural network [15]. The limit setting criterion of a maximum number of signal events for a fixed number of background events was adopted. The background level chosen was 0.4 events, corresponding to a 67% probability that no such events would be observed.

The set of cuts which optimally separates signal from background was determined by a systematic search using distributions of signal MC events. Many sets of selection criteria were explored. A cut on a single, relatively simple variable, $S_T \equiv H_T^e + H_T^j$, where $H_T^e \equiv E_T^{e1} + E_T^{e2}$ and $H_T^j \equiv \sum_{\text{jets}} E_T^j$, satisfied the limit setting criterion. Approximately 0.4 background events are expected for $S_T > 350$ GeV. No events remain in the base data sample after this S_T cut is applied. The highest value of S_T seen in the data is 312 GeV. The background which is roughly equally distributed among the three main sources is estimated to be 0.44 ± 0.06 events.

To investigate the background further, constrained mass fits were performed on the events in the base data sample, on background samples, and on the 200 GeV/c^2 leptoquark signal MC sample. The 3C mass fit was based on the SQUAW kinematic mass fitting program and required the two ej masses to be identical. Figures 1(a–c) show S_T as a function of the fit mass for the esti-

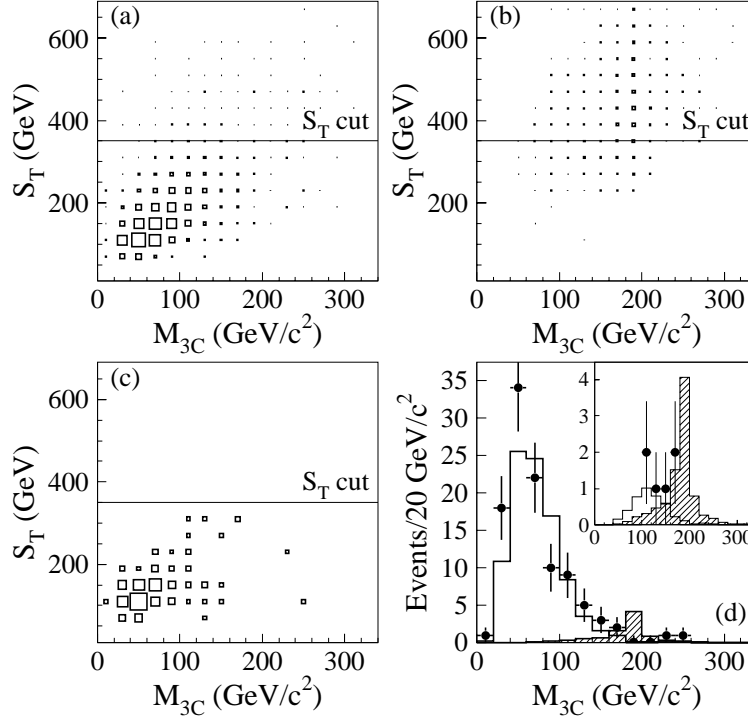


Fig. 1. S_T vs. 3C fit mass distributions for (a) background, (b) 200 GeV/c^2 leptoquarks, and (c) the base data sample. (d) Mass distribution of the data events (solid circles), expected background (solid line histogram), and 200 GeV/c^2 leptoquarks (hatched histogram). The inset plot shows these distributions for $S_T > 250$ GeV.

mated background, 200 GeV/c^2 leptoquark events, and the base data sample. The distribution from the data agrees with that of the expected background. Figure 1(d) shows the one dimensional mass distributions for the same samples. Inset in Fig. 1(d) are the same distributions after a cut on $S_T > 250$ GeV. As can be seen, the data are consistent with the background prediction.

The overall signal detection efficiency is 9–37% for leptoquark masses of 120–250 GeV/c^2 . A 95% confidence level (CL) upper limit on the cross section σ was set using a Bayesian approach with a flat prior distribution for the signal cross section. The statistical and systematic uncertainties on the efficiency, the integrated luminosity, and the background estimation were included in the limit calculation with Gaussian prior distributions. The resulting upper limit on the cross section is shown in Fig. 2 together with the NLO calculation of Ref. [13]. The intersection of our limit curve with the

lower edge of the theory band ($\mu = 2M_{LQ}$) is at $\sigma = 0.068$ pb, leading to a lower limit on the mass of a first generation scalar leptoquark of $225 \text{ GeV}/c^2$.

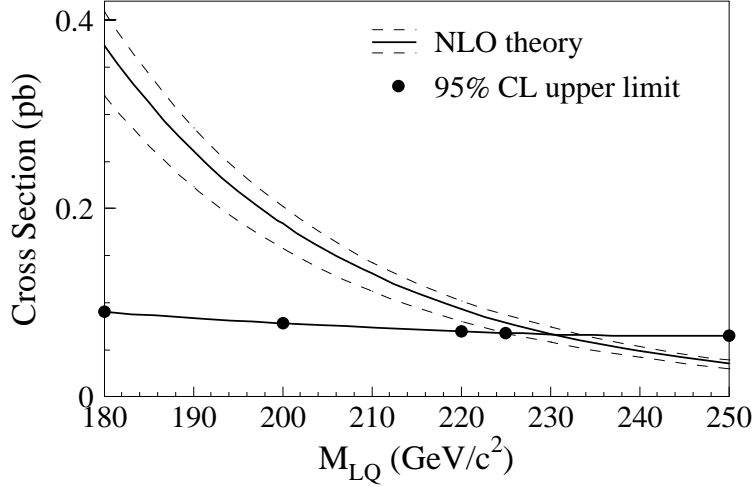


Fig. 2. Upper limit on the leptoquark pair production cross section for 100% decay to $e q$. Also shown is the NLO calculation [13] where the central solid line corresponds to $\mu = M_{LQ}$, and the lower and upper dashed lines to $\mu = M_{LQ}/2$ and $\mu = 2M_{LQ}$, respectively.

3 The $e\nu + \text{jets}$ Channel

A base data sample of 14 events with one electron, two or more jets, missing E_T ($\cancel{E}_T > 30 \text{ GeV}$), and $M_T^{e\nu} > 110 \text{ GeV}/c^2$ was selected. The estimated background is 17.8 ± 2.1 events, of which 11.7 ± 1.8 , 4.1 ± 0.9 , and 2.0 ± 0.7 events are from $W + \text{jets}$, QCD multijets, and $t\bar{t}$ production, respectively.

Monte Carlo samples similar to those in the $ee + \text{jets}$ were used in this analysis. The $W + \text{jets}$ background which is dominant prior to requiring $M_T^{e\nu} > 110 \text{ GeV}/c^2$ was simulated using the VECBOS program.

Two variables that provide significant discrimination between signal and remaining background were identified. They are the energy variable $S_T \equiv E_T^e + E_T^{j1} + E_T^{j2} + \cancel{E}_T$, where E_T^{j1} and E_T^{j2} are the transverse energies of the two jets, and a mass variable $\frac{dM}{dM}(M_{LQ}) \equiv \min(\frac{|M_{ej}^{(i)} - M_{LQ}|}{M_{LQ}}; i = 1, 2)$, where M_{LQ} is an assumed leptoquark mass and $M_{ej}^{(i)}$ are the invariant masses of the electron with the two jets.

To find the optimal selection cuts, the same criterion as in the $ee + \text{jets}$ analysis [10] of maximizing the signal efficiency for a fixed background of ≈ 0.4 events was adopted. In the low mass range ($M_{LQ} \leq 120 \text{ GeV}/c^2$), where the LQ production rates are high, requiring $S_T > 400 \text{ GeV}$ is sufficient. For $M_{LQ} > 120 \text{ GeV}/c^2$, neural networks (NN) were used since they provide higher efficiency than an S_T cut alone. At each mass where MC events were generated, a three layer feed-forward neural network [15] was used with two inputs (S_T and $\frac{dM}{M}(M_{LQ})$), five hidden nodes, and one output node. Each NN was trained using simulated LQ events as the signal (desired output $\mathcal{D}_{NN} = 1$) and a mixture of $t\bar{t}$, $W + \text{jets}$, and multijet events as background (with desired output $\mathcal{D}_{NN} = 0$). Cuts on \mathcal{D}_{NN} that yield background estimates in closest proximity to the desired background were obtained by varying \mathcal{D}_{NN} in steps of 0.05. The expected background after the cut ranges between 0.29 ± 0.25 and 0.61 ± 0.27 . No data events pass the cuts.

Figures 3 (a)-(c) show the 2-dim. distributions of $\frac{dM}{M}(180)$ vs. S_T for simulated LQ signal events with $M_{LQ} = 180 \text{ GeV}/c^2$, the combined background, and data. The contours corresponding to constant values of \mathcal{D}_{NN} demonstrate the separation achieved between signal and background. The distribution of \mathcal{D}_{NN} for data is compared with the predicted distributions for background and signal in Fig. 3 (d). The data are described well by background alone. The highest \mathcal{D}_{NN} observed in the final data sample is 0.79.

Using Bayesian statistics, a 95% CL upper limit on the leptoquark pair production cross section was obtained for $\beta = \frac{1}{2}$ as a function of leptoquark mass. The statistical and systematic uncertainties in the efficiency, the integrated luminosity, and background estimation were included in the limit calculation with Gaussian prior probabilities. The measured 95% CL cross section upper limits for various LQ masses are also plotted in Fig. 4 together with the NLO calculations [13] for $\beta = \frac{1}{2}$. The intersection of the limit curve with the lower edge of the theory band ($\mu = 2M_{LQ}$) is at 0.19 pb, leading to a 95% CL lower limit on the LQ mass of $175 \text{ GeV}/c^2$.

4 Combined Limits

An analysis of the $\nu\nu + \text{jets}$ channel is accomplished by making use of our published search ($\int L dt \approx 7.4 \text{ pb}^{-1}$) for the supersymmetric partner of the top quark [16]. Three events survive the selection criteria ($\cancel{E}_T > 40 \text{ GeV}$ and 2 jets with $E_T > 30 \text{ GeV}$) consistent with the estimated background of 3.5 ± 1.2 events. The signal efficiency for $M_{LQ} = 80 \text{ GeV}/c^2$ is calculated to be 2.2%. This analysis yields the limit $M_{LQ} > 79 \text{ GeV}/c^2$ at 95% CL for $\beta = 0$.

Combining the $ee + \text{jets}$, $e\nu + \text{jets}$, and $\nu\nu + \text{jets}$ channels, 95% CL upper limits on the LQ pair production cross section were calculated as a function of LQ mass for various values of β . These cross section limits for $\beta = \frac{1}{2}$ (shown in Fig. 4), when compared with NLO theory ($\mu = 2M_{LQ}$), yield a 95% CL lower limit on the LQ mass of $204 \text{ GeV}/c^2$. The lower limits on the LQ mass

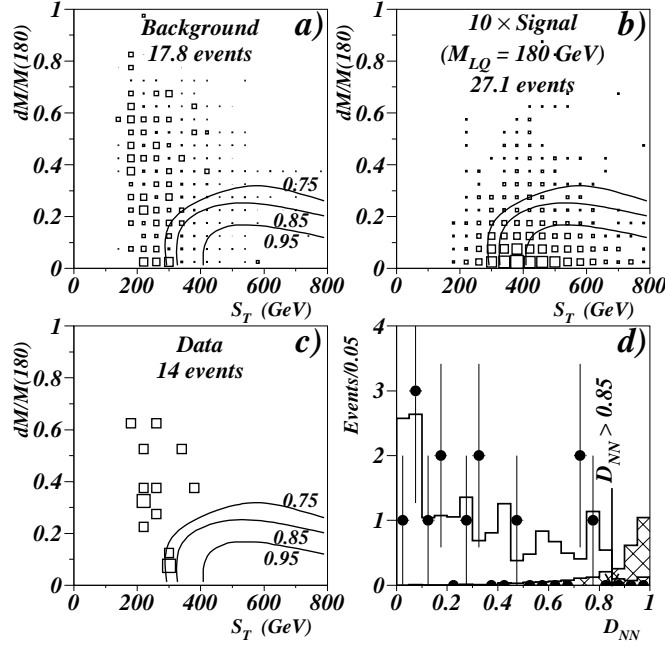


Fig. 3. $\frac{dM}{M}(180)$ vs. S_T distributions for (a) predicted background, (b) simulated LQ events ($M_{LQ} = 180 \text{ GeV}/c^2$), and (c) data, after all cuts except that on $D_{NN}(180)$. The contours correspond to $D_{NN} = 0.75$, 0.85 , and 0.95 . The area of a box is proportional to the number of events in the bin, with the total number of events normalized to 115 pb^{-1} . (d) Distributions of D_{NN} for data (solid circles), background (solid hist.) and expected LQ signal for $M_{LQ} = 180 \text{ GeV}/c^2$ (hatched hist.).

derived as a function of β , from all three channels combined as well as from the individual channels are shown in Fig. 5. These results can also be used to set limits on pair production of any heavy scalar particle decaying into a lepton and a quark, in a variety of models.

5 Conclusion

We have presented a search for first generation scalar leptoquark pairs in the $ee + \text{jets}$ and $e\nu + \text{jets}$ decay channels. Combining the results with those from the $\nu\nu + \text{jets}$ channel, we exclude at 95% CL leptoquarks with mass below $225 \text{ GeV}/c^2$ for $\beta = 1$, $204 \text{ GeV}/c^2$ for $\beta = \frac{1}{2}$, and $79 \text{ GeV}/c^2$ for $\beta = 0$. Our results exclude (at 95% CL) an interpretation of the HERA high Q^2

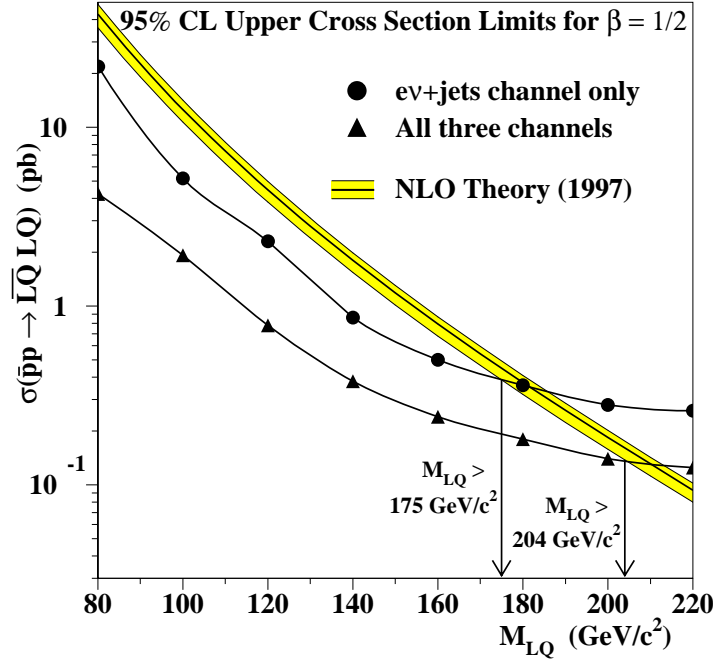


Fig. 4. Measured 95% CL upper limits on the leptoquark pair production cross section in the $e\nu$ + jets channel (circles) and all three channels combined (triangles) for $\beta = \frac{1}{2}$. Also shown are the NLO calculations of Ref. [13] where the central line corresponds to $\mu = M_{LQ}$, and the lower and upper lines to $\mu = 2M_{LQ}$ and $\mu = M_{LQ}/2$, respectively.

event excess via s -channel LQ production with LQ mass below $200 \text{ GeV}/c^2$ for values of $\beta > 0.4$.

6 Acknowledgements

I would like to express my appreciation to the organizers of this excellent conference. It is also my pleasure to thank my colleagues from DØ who helped me in preparing this report.

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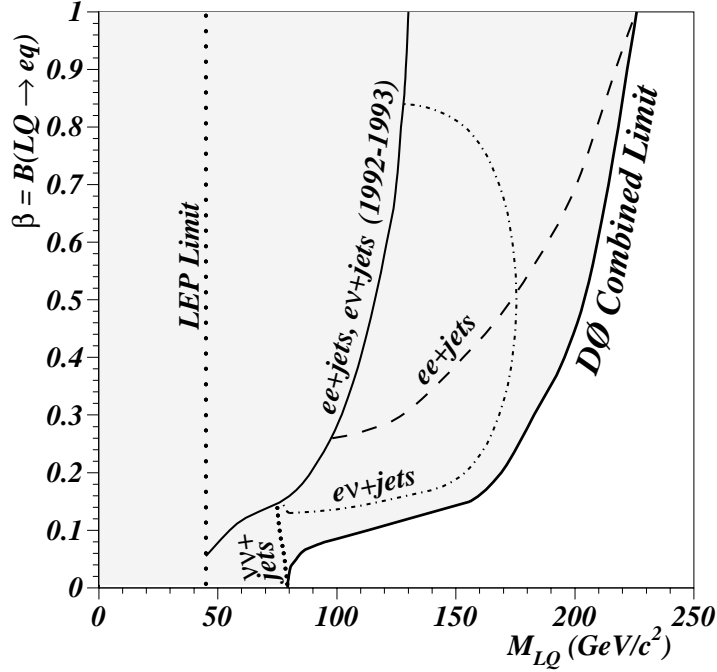


Fig. 5. Lower limits on the first generation scalar leptoquark mass as a function of β , based on searches in all three possible decay channels for leptoquark pairs. Limits from LEP experiments and from our previous analysis [7] of 1992-93 data are also shown. The shaded area is excluded at 95% CL.

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